Numerical Techniques and Cloud-Scale Processes for High-Resolution Models

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LONG-TERM GOALS

The long-term goal of this project is to improve the existing US Navy mesoscale atmospheric forecast model, the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®[1]) and maintain it at the leading edge of the Numerical Weather Prediction (NWP) models, while at the same time continue developing the next generation model. In the near future, a change of paradigm to unified approach in NWP will necessitate a novel approach in modeling.

OBJECTIVES

There are two main objectives, based on the targets. First, to continue development of the model based on the Spectral Element (SE) methods and evaluate detailed simulations in two-dimensions (2D) and preliminary tests in three dimensions (3D). In addition, improvements to the numerical temporal integration scheme will be sought. Second, to improve the current generation version of COAMPS by implementing state-of-the-science numerical methods such as Weighted Essentially Non-Oscillatory (WENO) based methods for tracer transport and semi-lagrangian time stepping for improved model efficiency. The overarching objective is to develop a dynamical core suitable for the unified approach in support of NWP.

APPROACH

In our two-pronged approach we will leverage our efforts to advance both the SE model and COAMPS.

1. SE Model

   We will follow a systematical plan to develop and test the new model based on the SE methods. Many aspects of using the SE model in the atmospheric science are new so consistency of the numerical results compared to known solution is of vital importance. The SE model will be evaluated by methodically mapping out the input parameter space of element number (*h*) and polynomial order (*p*), which combined determine the spatial resolution. We will use two

[1]COAMPS® is a registered trademark of the Naval Research Laboratory.

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idealized two-dimensional test cases to assess the sensitivity of the SE model to the setup parameters. We will also start testing the code in three dimensions. In addition, a few new time-integration schemes with optimal stability properties will be tested as a possible alternative to the semi-implicit second order backward difference (BDF2) method.

2. COAMPS

   Atmospheric models require numerical methods that can accurately represent the transport of tracers with steep gradients, such as those that occur at cloud boundaries or the edges of chemical plumes. In atmospheric sciences, the most widely used numerical techniques for this type of problem are flux-corrected transport or closely related flux-limiter methods. The limiters are typically designed to prevent the development of new extrema in the concentration field. WENO methods are widely used in many disciplines, but scarcely been tested in atmospheric applications. Our approach has been to carefully test the WENO-based scheme for a variety of idealized and real-data scenarios.

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WORK COMPLETED

We have completed an in-depth analysis of the sensitivity of the simulation results to the setup parameters for two idealized two-dimensional test cases. The *h-p* parameter space was systematically mapped out resulting in 91 pairs of setup parameters *h* and *p*. The average spatial resolution, defined as the average nodal spacing within the element, varied from 200 m to 10 km in horizontal and 40 m to 1500 m in vertical direction. The first test represents a flow over a small hill, resulting in a linear, hydrostatic mountain wave for which an analytic solution is known and simulation results are quantitatively assessed. The second test is a simulation of an idealized mid-latitude squall line, triggered by a thermal bubble at the start of the simulation. The storm evolution and characteristic quantities, such as precipitation accumulation, are evaluated. We have also completed a preliminary series of three-dimensional simulations of an idealized flow over an isolated mountain. Four alternative implicit-explicit time integration schemes with desirable overall stability properties were tested on a few idealized two-dimensional cases and compared to the existing scheme (BDF2) in terms of maximum stable time step and elapsed wallclock time.

The WENO based selective monotonic advection (SMA) scheme (Blossey and Durran, 2007) has been fully implemented in COAMPS. In addition, a semi-Lagrangian option (Skamarock, 2006; Blossey and Durran, 2007) has also been implemented in order to offset the extra computational costs required for the SMA scheme. Both the semi-Lagrangian and Eulerian versions of the SMA scheme were tested and compared with the currently available 2nd- and 4th-order finite difference advection schemes for a variety of idealized and real data test problems.

RESULTS

The results of the SE model for a linear, hydrostatic mountain wave suggest that the model is computationally more expensive at the same resolution compared to a finite-difference model. If an *apriori* acceptable value of error is known, the SE model is less expensive because it achieves the

desired accuracy at a coarser resolution. Refining the spatial resolution by increasing the polynomial order, number of elements, or both, becomes computationally expensive and is no longer justified as soon as the nominal grid spacing is adequate to resolve the simulated phenomenon.

The squall line simulations confirm the robustness of the SE model across the parameter space, when the storm is adequately resolved. With no analytic solution available, we compared the storm evolution and some selected integrated quantities. When the average nodal spacing is adequate to describe the physical phenomenon, the results over the parameter space look very similar (Fig 1), with similar conclusions for other values of the nominal spacing.

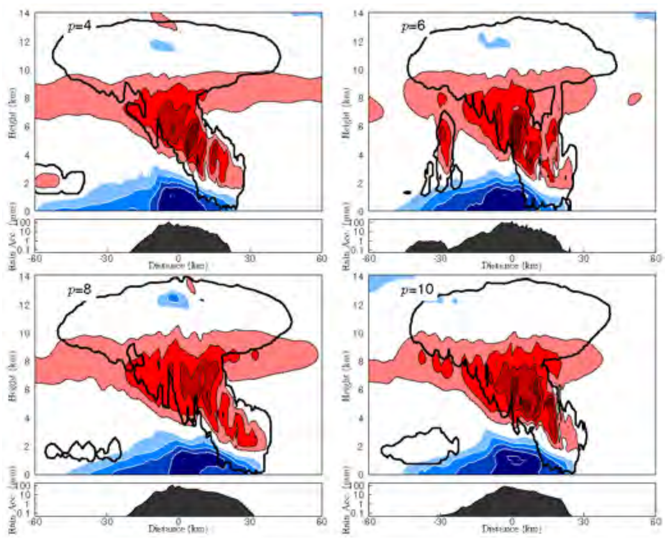

Figure 1: Vertical cross sections of the squall line evolution at t=6000 s with the nominal spacing Δx=1 km. The polynomial order varies as follows: p=4 (top left panel), p=6 (top right panel), p=8 (bottom left panel), p=10 (bottom right panel). Filled contours represent equivalent potential temperature perturbation (contour interval 3 K), with red (blue) shading representing positive (negative) values. The interval centered around zero ([-3, 3]) is omitted. The cloud mixing ratio (q_c=10^{-5}) in thick black line represent the cloud outline. The bottom portion of each panel shows rain water accumulation as a function of distance.

Unlike for the dry simulations, refining the nominal resolution does not result in convergence of solutions. A noticeable trend in some integrated quantities, such as a decrease of rainfall accumulation (Fig 2) and maximum rain rate with the increased resolution and an increase of maximum vertical velocity can be attributed to nonlinearity of moist processes. As the grid spacing gets finer, the scale of instabilities is refined as well. Instead of a large updraft, there are many smaller cells with more intense vertical velocities. Their overall combined effect, in terms of the mass flux or transport of moisture from the surface layer into the convective cell, and subsequent cloud processes (e.g. water vapor condensation with the latent heat release), is smaller compared to a larger updraft, resulting in reduced precipitation rates and consequently less accumulated precipitation.

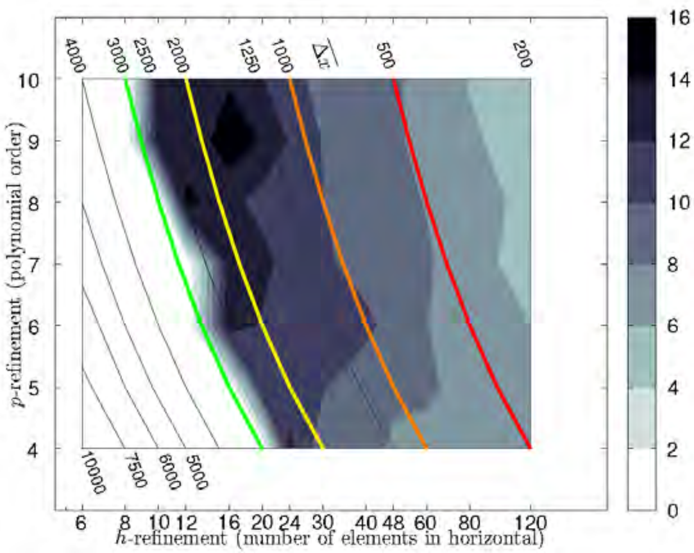

Figure 2: Total rainfall accumulation (mm) in 6 hours averaged over the entire domain as a function of the polynomial order (p) and number of elements in horizontal (h) for the squall line simulations. Curved color lines represent constant nominal horizontal resolution (Δx, or constant number of nodal points in the horizontal direction): green (Δx=3 km), yellow (Δx=2 km), orange (Δx=1 km) and red (Δx=0.5 km).

To provide further evidence, we performed a horizontal spectral analysis of the vertical velocity, averaged over time and height (Fig 3). In the original set of simulations (Fig 3, left panel), we noticed that with the increasing resolution the peak of the power spectrum moved towards shorter scales. We performed an additional set of "dry" simulations with no moisture and the resulting power spectra coincide regardless of the spatial resolution (Fig 3, right panel).

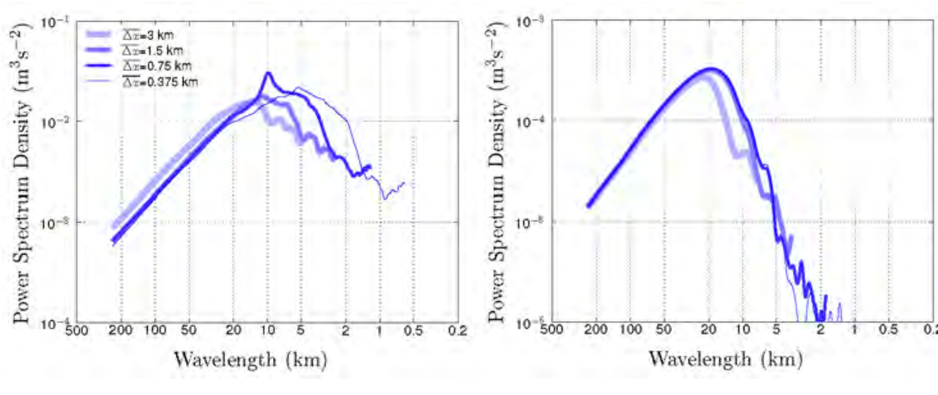

Figure 3: Power spectra for simulations with p=8 and varying nominal resolutions Δx=3 km (thickest, lightest blue), Δx=1.5 km (thick, light blue), Δx=0.75 km (thin, dark blue) and Δx=0.375 km (thinnest, darkest blue). The left panel is for the control squall line simulations and the right panel is for the "dry" squall line with no moisture. The spectra are averaged over height (0-12 km, with 0.5 km increment) and time (0-4 h, with 300 s increment).

The SE model has been expanded and is currently being tested in three dimensions (e.g., flow over an isolated mountain is shown in Fig. 4). In addition, preliminary tests of scaling on massively parallel computational platforms are also being evaluated.

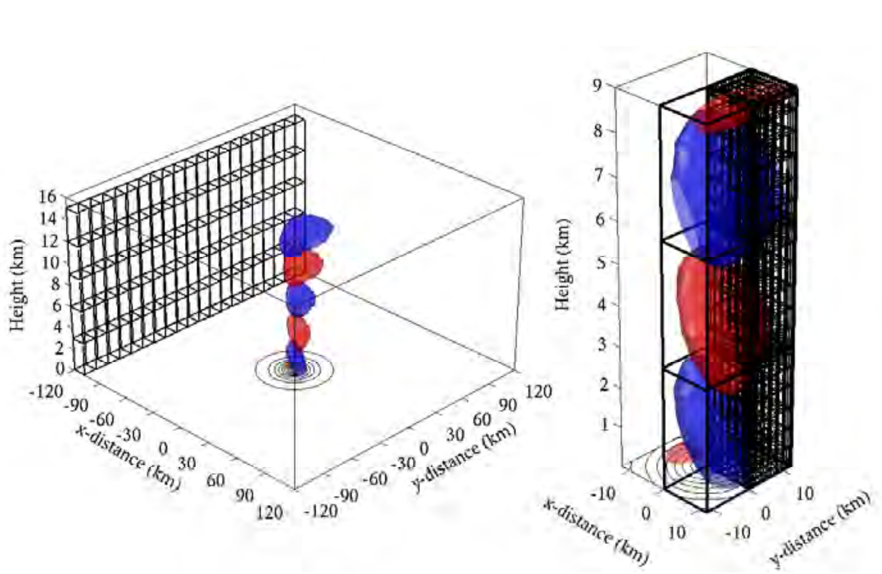

Figure 4: Linear, inviscid hydrostatic flow over an idealized 3D mountain (circular terrain contours are visible in the x-y plane). Isosurfaces of vertical velocity perturbation with red (blue) color representing positive (negative) value of 0.001 m s-1. The full horizontal extent of the domain with element structure in the background (left panel) and a detailed cross-section at the center of the domain showing the nodal points within a few elements.

Four additional time integration schemes were tested using an idealized 2D test case (Schaer mountain). Some candidate schemes allowed for approximately double the time step permitted by the currently used BDF2 scheme, but the overall time to finish the simulation was in a couple of cases much longer (bdf23n and am2sax32). It is interesting to note that the overall fastest execution time was achieved by the mcnax32 scheme when using the same time step as bdf2. Longer time steps cause more iterations while solving a system of linear equations.

Table 1: Time integration schemes with the maximum stability permissible time step and total execution time for a simulation lasting 50000s.

Scheme name	Maximum stable time step dt	Walltime to execute
bdf2 (default)	dt = 4 s	2379 s
bdf23n	dt = 7.6 s	3142 s
am2sax32	dt = 8.4 s	3981 s
mcnax32	dt = 7.6 s	2120 s
mcnax32	dt = 4 s	1581 s

Figure 5 shows results from a series of two-dimensional mid-latitude squall line simulations for the WENO based selective monotonic advection scheme in COAMPS. Plotted is a one-hour average vertical cross section of simulated cloud-liquid water, rain water, and negative potential temperature perturbations. While differences exist between the 4th-order advection scheme (Fig. 5a) and the SMA scheme (Fig. 5b), the overall qualitative behavior is similar. Both the 4th-order advection and the SMA scheme contain a compact convective updraft, spreading low-level cold pool near the surface, and a broad anvil in the upper troposphere. Figures 5cd show results from a similar two-dimensional squall-line simulation but with the semi-lagrangian scheme. The simulation with a time step two-times as long as the control (Fig. 5c) is qualitatively similar to the Eulerian versions of the code. On the other hand, as the length of the time step increases, intensity of the squall decreases and the spreading of the anvil is limited in the upper troposphere (Fig. 5d).

One drawback of the SMA scheme is the extra computational overhead required to maintain monotonicity. For example, the SMA squall-line simulation requires approximately 25% more cpu time than the similar 4th-order advection solution. Fortunately, switch from the Eulerian framework to the semi-lagrangian framework can help minimize the extra computational burden. The run time for the 4dt semi-lagrangian simulation is only 12% longer than the 4th-order advection solution. It is expected further improvements in timing will be realized for the semi-lagrangian scheme as more scalar variables are included and the domain expanded to three dimensions.

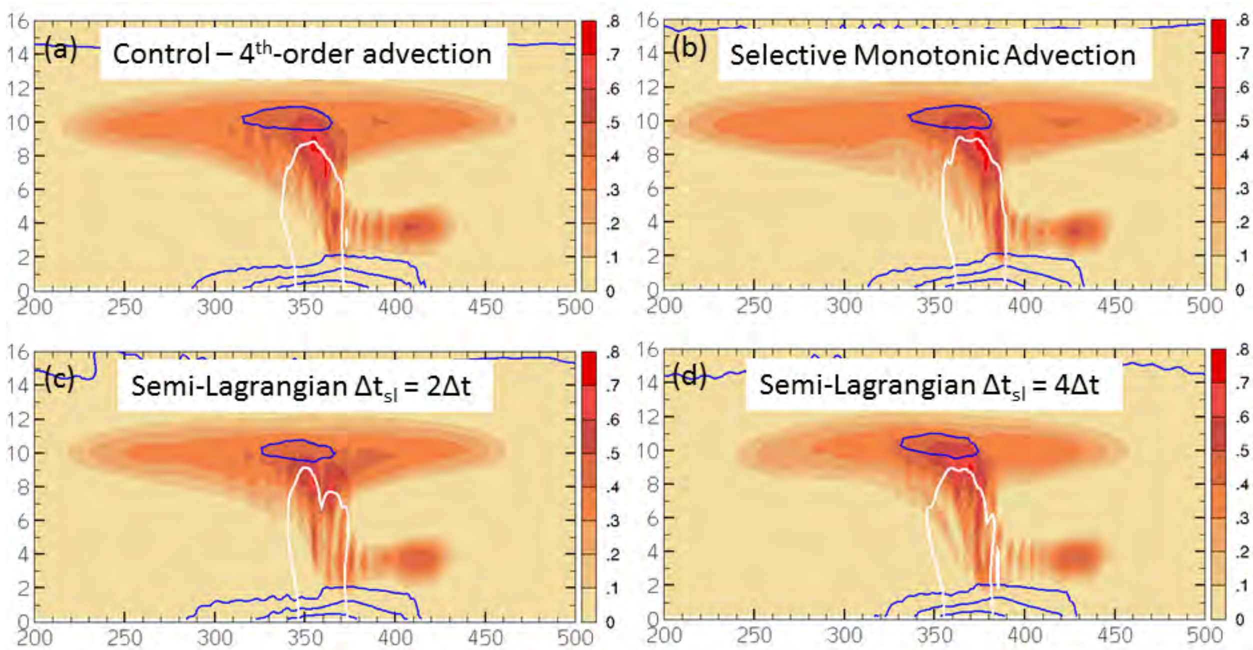

Figure 5. One-hour average vertical cross section of a two-dimensional squall simulation with (a) fourth-order advection, (b) selective monotonic advection, (c) selective monotonic advection with a semi-lagrangian time step that is 2- times the time step of (b), and (d) same as (c) except the time step is 4-times the time step of (b). Plotted is the mixing ratio for cloud liquid water (filled, ci=0.1 g/kg) and 0.25 g/kg rain water contour (white) as well as negative perturbation potential temperature (blue; ci=2 K).

IMPACT/APPLICATIONS

COAMPS is the Navy's operational mesoscale NWP system and is recognized as the key model component driving a variety of DoD tactical decision aids. Accurate mesoscale prediction is considered an indispensable capability for defense and civilian applications. Skillful COAMPS predictions at resolutions less than 1 km will establish new capabilities for the support of the warfighter and Sea Power 21. The SE model could become the unified dynamical core for both global and mesoscale weather forecasts of the US Navy. The design of the model and its structure are such that it will take a full advantage of available computational cores as they become available in large numbers (~100000) in the near future.

TRANSITIONS

The next generation COAMPS system will transition to 6.4 projects within PE 0603207N (SPAWAR, PMW-120) that focus on the transition COAMPS to FNMOC. The improvements to the COAMPS dynamical core have been transitioned to the SPAWAR 6.4 project and subsequently to operations as a result of the marked improvement in the geopotential height bias statistics.

RELATED PROJECTS

COAMPS will be used in related 6.1 projects within PE 0601153N that include studies of air-ocean coupling, boundary layer studies, and topographic flows and in related 6.2 projects within PE 0602435N that focus on the development of the atmospheric components (QC, analysis, initialization, and forecast model) of COAMPS.

PUBLICATIONS

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Gabersek, S., Doyle, J. and Giraldo, F., 2011: Dry and Moist Idealized Experiments With a Two-Dimensional Spectral Element Model, submitted to Monthly Weather Review